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Observation-Based Dissipation and Input Terms for Spectral Wave Models, with End-User Testing

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LONG-TERM GOALS

The long-term goal is to implement input and dissipation source functions, based on advanced understanding of physics of air-sea interactions, wave breaking and swell attenuation, in wave-forecast models.

OBJECTIVES

The objectives are to use new observation-based source terms for the wind input, wave-breaking (whitecapping) dissipation and swell decay in the third-generation models WAVEWATCHIII and SWAN. Calibration and performance of the source functions have to satisfy a set of physical constraints, and methodology is to be developed to enable testing the source functions separately before they are blended in the full model. Verification is to be conducted by means of academic tests and hindcasting real-life scenarios defined by the end users from the US Navy, Army and NOAA, to include deep and finite-depth conditions, closed seas (no swell) and open ocean, extreme weather events, and global simulations.

APPROACH

Physics of two primary source/sink terms employed by the operational models, namely wave-breaking energy dissipation and wind-to-wave energy input have not been updated for decades. In the meantime, the new physics is available. For the first time under field conditions, in the course

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of the ONR Lake George (Australia) project, estimates of the spectral distribution of the wave-breaking dissipation were obtained, and measurements of the wind-input spectral function were conducted at moderate-to-strong wind forcing (Young et al., 2005). Corresponding outcomes were parameterised as source functions suitable for spectral wave models, and both exhibit a number of physical features presently not accounted for.

For the dissipation, these are threshold behaviour of breaking/dissipation in terms of wave-steepness/spectral-density, cumulative effect at scales smaller than the spectral peak, and direct coupling of the dissipation rates with input rates at very-strong/extreme wind forcing. Bi-modal directional distribution of the dissipation was also observed (Babanin et al., 2001, Babanin and Young, 2005, Young and Babanin, 2006a, Babanin et al., 2010). None of these features are present in the currently employed dissipation functions used for operational wave forecasting.

The new wind-input features are the non-linear behaviour of the input term (that is, the input rates depend on wave steepness) and full flow separation in extreme conditions (that is, relative slowing down of the wind-wave exchange in steep-waves/strong-winds circumstances) (Donelan et al., 2005, 2006, Tsagareli et al., 2010). Enhancement of the wind input due to wave breaking was also observed, quantified and parameterised (Babanin et al., 2007).

In the above-mentioned field measurements of the wind input, only the conditions of waves produced by the wind were observed. In real oceanic situations, there can occur conditions of the wind being adverse to the waves, either fully or in some parts of the wave directional spectrum. In such conditions, the waves have been measured to pass the energy and momentum back to the wind. In order to accommodate this physics, parameterisation of the negative input was incorporated, according to laboratory measurements of Donelan (1999) fulfilled in the same instrumental, theoretical and parametric framework as Donelan et al. (2006).

While the wind input and dissipation are the main source/sink energy terms in the model, the latter has to be subdivided into separate terms: one term in case of breaking waves (for wind-generated waves), and another for non-breaking waves (swell). The first one (whitecapping dissipation) turns zero once the spectral density at a particular scale drops below the threshold as mentioned above, and a much weaker dissipation accompanies swell propagation across the ocean. Recently, two new swell-dissipation terms were suggested, which imply different physics: interaction of swell with atmospheric boundary layer (Ardhuin et al., 2009) and with background turbulence (Babanin, 2006, 2011, 2012a).

The project will use both the new source terms and a new approach to their validation. The main feature of the approach is stringent physical constraints on the momentum/energy fluxes in and out the wave system: that is, the integrated momentum wind input must not exceed independently known total stress, and the integrated dissipation must constitute the experimentally known proportion with respect to the total input. For the total dissipation, independent parameterisations based on profile measurements of volumetric dissipation rates are also available. Such constraints, first of all, are necessary to make the source functions physically consistent, and most importantly, they allow to calibrate the input and dissipation one by one, before they incorporated in the model where their contributions are not possible to separate (Babanin et al., 2005, 2010, Tsagareli et al., 2010, Rogers et al., 2012).

Work on the physical constraints is continuing. For the total stress, a number of new dependences on the properties of waves and atmospheric boundary layer have been identified (see Work Completed below). For the ratio of dissipation and input, the previous experimental guidance was the work of Donelan (1998). Recent research in NRL, however, indicates that the ratio should be essentially less (see Results below).

For practical testing and hindcasting, a set of field sites and datasets were chosen which include Lake Michigan (deep water, no swell, Rogers et al., 2012), Lake George (finite depth, no swell,

Young and Verhagen, 1996, Young et al., 2005), Gulf of Mexico (open sea, deep-to-finite depths, swell, hurricanes, IPET, 2006, Smith, 2006) and a selection of tropical cyclones from the Australian region (Young, 2006, Babanin et al. 2011). Measurement data are available for all the chosen sites. Now that the model is fully tested, global simulations for 2006 are being performed and compared with the altimeter database (Zieger et al. 2009) and with NOAA simulations based on the previous version of WAVEWATCH III (Chawla et al., 2011). These data are also used for validation of the tropical-cyclone modelling results.

The research group includes academics from Swinburne University of Technology (SUT), US Naval Research Laboratory (NRL), US Army Corps of Engineers (CHL) and US Weather Service (NOAA). SUT group consists of Alex Babanin and Ian Young who had developed the new dissipation term and participated in development and testing of the new wind-input term in the course of the earlier ONR project, and Stefan Zieger, Research Fellow employed on the current project. This group conducts bulk of the academic research and implementation of the new source terms into WW3, the latter in collaboration with Hendrik Tolman from NOAA and Erick Rogers from NRL. Erick Rogers, and Jane Smith from CHL contribute to the project goals in the development and verification of the new physical formulations, to replace the formulations currently used in Navy and Army operational models. A specific goal of NRL and CHL is to create models that are physically consistent with what we know about the real ocean, while at the same time ensuring that the new models are optimal for Navy and Army applications. NRL and CHL have also implemented the new input and dissipation terms into SWAN, apart from WW3, and participate in the development of validation/calibration cases, and in particular those of extreme conditions observed in the Gulf of Mexico.

WORK COMPLETED

This is a report for the third year of the project. In the first year, the formulations for the observation-based source terms, were validated, individually calibrated, and tested together in a two-dimensional wave research model with exact computations of the non-linear interaction term (Tsagareli et al. 2010, Babanin et al. 2010). The new source terms and the physical-constraint approach were implemented in SWAN and tested by means of the Lake Michigan and a selection of the Gulf of Mexico cases. Field data sets for further model-testing were selected and prepared: Lake George; Black Sea; global altimeter data base.

During the second year, the main aim of the project was implementation of the source functions into WW3. This was done, and academic testing and initial field validation of the model were concluded (Zieger et al., 2011). In addition, the model performs an automatic self-correction routine by comparing the input total stress with the integral of the wind input over the computed spectrum at each time step. Research on other topics of the project also continued. These included breaking and dissipation, sea drag, wave-bottom friction, wave-turbulence and its role in the swell dissipation. Particular attention was paid to preparing for future hurricane modelling and global simulations. The global altimeter database, earlier developed, was used for investigating the global trends of waves and winds over the past 25 years.

In the third year (current), the broad and intensive testing of the new version of the model was started, by means of hindcasting. In order to apply the model to the ocean, it required adding auxiliary source terms, for swell dissipation (Babanin, 2011, 2012a) and for negative wind input (interaction with adverse components of the wind, following Donelan (1999)). This full model was then applied to Lake Michigan (i.e. no-swell conditions) and Tropical Cyclone Yasi (full physics test). Testing the model by means of hurricanes of the Gulf of Mexico is now in progress. Based on these tests, new physics will be extensively verified. Also in progress is a full-year global hindcast for 2006. This hindcast will allow test the model for systematic biases (see Figure 3 below).

Research on the other topics of the project continued. Rogers et al. (2012) published the implementation and testing of the new source terms in SWAN model. Rogers and van Vleder (2012) investigated role of the nonlinear solver in wave models in reproducing the frequency bandwidth of wave spectra. Belski et al. (2012) used WAM combined with a 3D ocean circulation model, turbulence model with a wave-turbulence module, and bottom-sediment model to simulate sediment re-suspension. Babanin et al. (2011) published results of laboratory experiments of waves on opposing accelerating currents and following decelerating current, which showed rapid downshifting of the wave energy to the lower sideband – a fully nonlinear effect presently not accounted for in the wave models. Study of wave breaking and dissipation continued in papers by Chalikov and Babanin (2012) (modelling the breaking in spectral environments), and by Galchenko et al. (2012) (laboratory investigation of wave influence on modulational instability, breaking and dissipation).

In 2012, PI Babanin led a special issue of the Journal of Geophysical Research on ocean waves and wave-coupled effects in lower atmosphere and upper ocean, and a number of papers by PIs were published in this issue. Babanin et al. (2012) is a review of the current state of this topic. On the topic of sea drag, Ting et al. (2012) investigated dependence of the drag on wave directionality and Toffoli et al. (2012a) on air humidity and finite-depth influences. For the upper-ocean wave effects and wave dissipation due to interaction with oceanic turbulence, Babanin and Chalikov (2012) developed a fully-nonlinear wave model coupled with a model for 3D turbulence, first of its kind. On this topic, Toffoli et al. (2012b) investigated response of the mixed layer to the tropical-cyclone waves. Young et al. (2012) published results on the trends of extreme values of the wind speed and wave height based on 25 years of global altimeter observations.

Two invited papers were published. Babanin (2012b) is a review of the new observation-based physics in spectral wave models for the ECMWF (European Centre for Medium-range Weather Forecast) workshop on wave modelling. Babanin (2012c) is a review of wave-coupled effects in the atmosphere and ocean for a coastal engineering meeting in Taiwan.

RESULTS

The results already submitted, accepted for publication or published and their significance are mentioned in sections Work Completed, Impact/Applications and more details can be viewed through the references in Publications section of this report. In this section, due to limited space, we will outline results achieved, but not published yet.

The main aim of the project at the current stage is a comprehensive testing of the new physics implemented in WAVEWATCH-III. The new version of WW3 is called BYDRZ (abbreviation for Babanin-Young-Donelan-Rogers-Zieger). In BYDRZ one can select between two versions of the swell-dissipation term, i.e. after Ardhuin et al. (2010) (hereinafter SWL4) and after Babanin (2012a) (hereinafter SWL6). Note that in Lake Michigan the seas re usually very young and therefore the effect of swell (mature sea state) is small. Thus, the Lake Michigan hindcast is a convenient test to quantify the robustness of the parameterisation. Following the analysis of Rogers and Wang (2007), performance of the parameterisation of the new observation-based input and dissipation BYDRZ terms is synthesised in Table 1. For comparisons, additional model runs were conducted with the Tolman and Chalikov (1996) physics (TC96) and with Ardhuin et al. (2010) parameterisation (TEST451). TC96 source terms largely underestimate wave height in the hindcast, for which the regression forced through the origin yields a 0.87 slope and an average bias of -9cm (see Table 1). The more recent parameterisation by Ardhuin et al. (2010) has a better skill, it increases the slope up to 0.92 and reduces the underestimation in wave height. It is noteworthy that the root-mean-square error significantly improved, when switching from TC96 to TTEST451. Results for the new observation-based source terms (BYDRZ) are similar to TEST451. As for the wave period, the model skill largely improves in the course of transition from the WAVEWATCH-

III default physics (TC96) to the more recent versions. Figure 1 depicts the probability scatter plots for BYDRZ SWL6 physics for various wave parameters, namely: wave height, mean wave period, mean wave direction, true peak period, and $T_{0,2}$ and $T_{-1,0}$ periods.

Table 1. Statistics for wave height and wave period for various source terms. Lake Michigan hindcast

wave height	**TC96**	**TEST451**	**BYDRZ SWL4**	**BYDRZ SWL6**
buoy no.	1685	1685	1685	1685
correlation	0.94	0.96	0.95	0.95
rms error	0.22	0.18	0.18	0.18
bias	-0.09	-0.05	0.01	-0.00
scatter index	0.22	0.18	0.20	0.19
slope (origin)	0.87	0.92	1.01	1.00
wave period $T_{-1,0}$				
correlation	0.90	0.92	0.90	0.91
rms error	0.48	0.33	0.36	0.35
bias	-0.30	-0.06	-0.01	-0.04
scatter index	0.09	0.08	0.09	0.08
slope (origin)	0.92	0.98	0.99	0.99

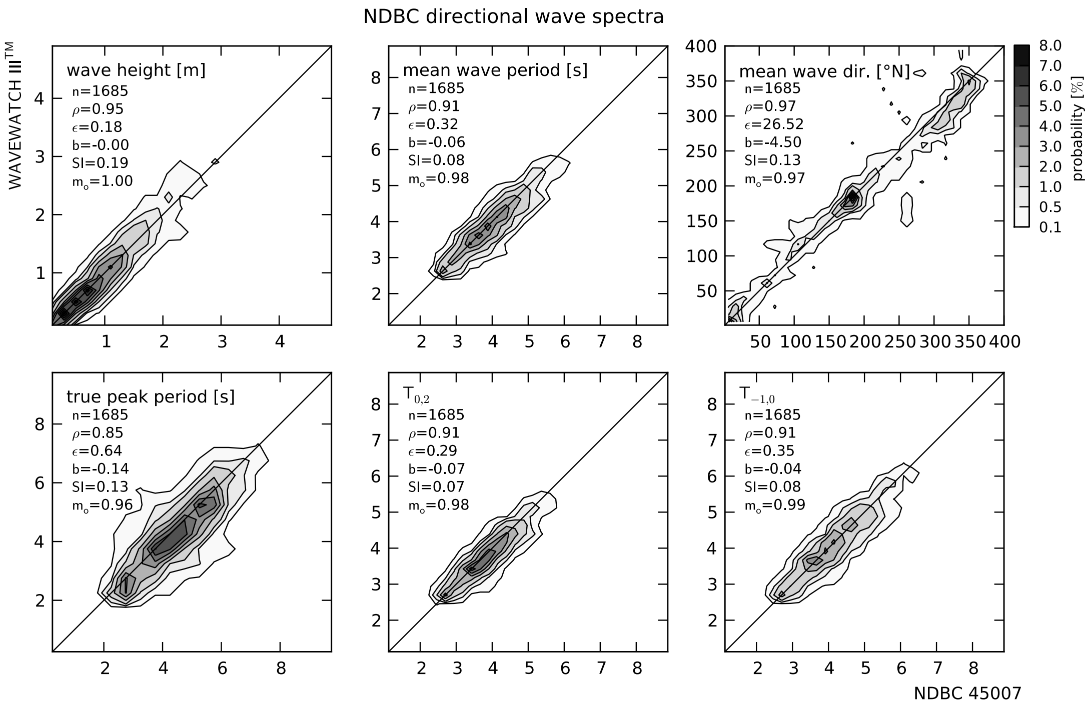

Figure 1. Probability scatter plots for wave height, mean wave direction and various weighted wave periods. Horizontal scale corresponds to measurements by the NODC buoy 45007 and the vertical scale to WW3 hindcast, using BYDRZ SWL6 physics, over the period of 1 Sep. – 14 Nov. 2002. Statistics in the legend include: number of observation (n), correlation (ρ), rms error (ε), bias (b), scatter index (SI) and slope though origin (m_o)

In Figure 2, performance of the BYDRZ source terms is tested by means of simulations of Tropical Cyclone Yasi (2011), one of the most powerful in Australian history. It crossed the Great Barrier Reef and therefore simulations in the deep and shallow waters essentially model two very different circumstances.

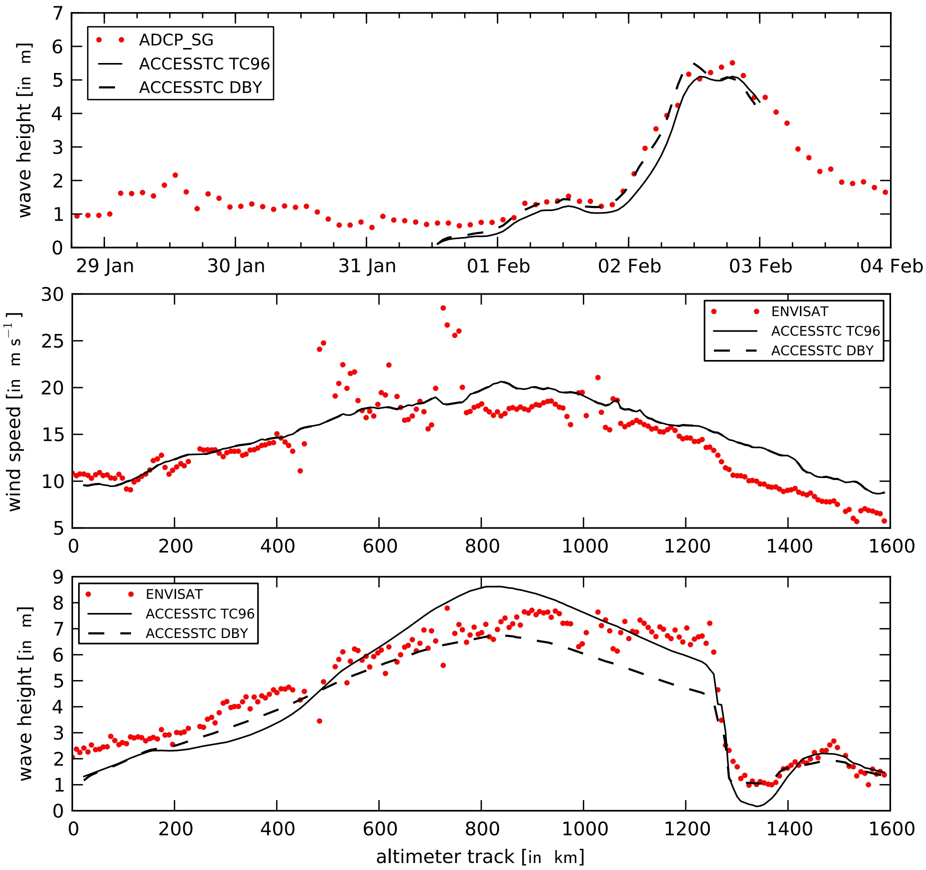

Figure 2. Validation of BYDRZ source terms by means of simulation of Tropical Cyclone Yasi. (Top) wave height time series recorded in shallow water near Townsville, QLD (146.97E, 19.1S). (Middle) performance of the wind product (ACCESS-TC atmospheric model, Bureau of Meteorology, Melbourne, Australia) used to drive simulation. (Bottom) wave height as recorded by ENVISAT altimeter in deep water on 1 Feb 2336 UTC.

Figure 3 shows preliminary results of BYDRZ SWL6 performance at the global scale. This simulation was carried out on 1x1.25 degree resolution grid, is driven by NOGAPS winds and CFSR sea ice, and the left panel uses the same legend as the Lake Michigan Figure 1. Global comparisons are validated against JASON1 altimeter data for the full duration of year 2006. In this comparison, the altimeter track was interpolated onto the model grid and then differences are grouped in 2x2 degree bins for visualisation (Figure 3, right panel).

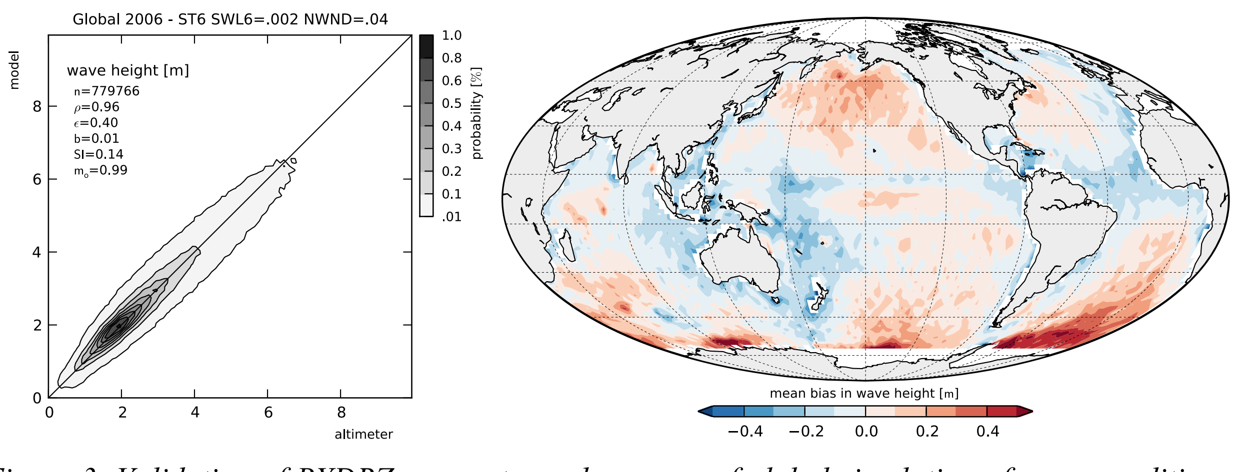

Figure 3. Validation of BYDRZ source terms by means of global simulation of wave conditions in 2006. Results are depicted in the form of (left) probability scatter plot between model and JASON1 altimeter wave heights and (right) the global bias as a function of latitude and longitude.

IMPACT/APPLICATIONS

Economic Development and Quality of Life

The impacts of the outcomes, outlined below, pertain to applications relating to improving the wave forecast, and will result in Economic Developments, such as increased efficiency of coastal and offshore industries, marine waterways, and Quality of Life, such as safety in coastal and open-sea areas, recreational activities at sea, management of coastline.

Paper by Rogers et al. (2012) is implementation of the new wind-input and whitecapping-dissipation functions in SWAN model. New swell-decay function developed by Babanin (2011, 2012a) is based on measurements and modelling of wave-turbulence interactions, a phenomenon not accounted for before. This dissipation is further studied numerically and experimentally by Babanin and Chalikov (2012) and Toffoli et al. (2012b), respectively. The coupled model of fully nonlinear waves and turbulence by Babanin and Chalikov (2012) is the first of its kind. Ting et al. (2012), Toffoli et al. (2012) provided novel dependences of the drag coefficient on wave directional spectrum, humidity and water depth, previously not accounted for. Roger and van Vledder (2012) showed the impact of the nonlinear term in wave models on their spectrum output. New bottom-friction routine was developed and introduced in SWAN which accounts for sediment size and provides dynamic coupling of the ripple-caused friction with the waves (Smith, G., 2012). New features of wave breaking and dissipation investigated numerically and experimentally by Chalikov and Babanin (2012) and Galchenko et al. (2012), respectively. Young et al. (2012) obtained trends for 100-year return winds and waves. Potential impact of this research is significant across variety of related topics.

TRANSITIONS

Economic Development and Quality of Life

As with Impact/Applications above, the transitions pertain to applications relating to improving the wave forecast, and will result in Economic Developments, such as increased efficiency of coastal and offshore industries, marine waterways, and Quality of Life, such as safety in coastal and open-sea areas, recreational activities at sea, management of coastline.

The new physics is implemented in SWAN (Rogers et al., 2012) which is now a default version in NRL. They are also used in research wave models at the University of Darmstatd, Germany and the National Cheng Kung University, Taiwan. SWAN with the new physics is now being applied routinely in coupled modeling at NRL-Stennis (Smith, T., et al., 2012) and is part of a FY12 transition to NAVOCEANO (Allard et al., 2012).

PI Rogers is applying knowledge gained in this project to other projects. In particular, recent analysis and improvement of the accuracy of the total input and dissipation predicted by these models has proven useful in two regards. First, these quantities are of primary importance in the context of momentum exchanges between models, and so this plays a key role in planning the next generation of coupled modelling systems (Earth System Prediction Capability, ESPC). Second, improved confidence in predictions of total dissipation is a prerequisite to applying associated model output quantities in the interpretation of data from the NRL WINDSAT radiometer (see Anguelova et al. in Related Projects listing).

RELATED PROJECTS

Allard, R.A., Smith, T.A., Jensen, T.G., Chu, P.Y., Rogers, W.E., Campbell, T.J. "Coupled Air-Ocean-Wave Prediction System Verification and Validation". SPAWAR 6.4. Joint publication (Allard et al., 2012, Smith, T., et al, 2012)

Anguelova, M., Dowgiallo, D., Smith, Geoffrey, Hwang, P., Means, S., Rogers, E. “"Oceanic Whitecaps as a Surface Expression of Under- and Above-Water Processes: Toward an Integral Remote Sensing of the Air-Sea Interface". NRL Core 6.1

Ardhuin et al. “Ocean Wave Dissipation and Energy Balance toward Reliable Spectra and First Breaking Statistics”. NOPP project, implements new dissipation function based on similar physical principles. Joint publications (Ardhuin et al., 2010, Filipot et al., 2010)

Babanin, A.V., Phillips, W.R.C., Ganopolski, A. “Wave-induced upper-ocean mixing”, Australian Research Council (ARC) Discovery grant. Investigation of the wave-induced turbulence and non-breaking dissipation (Babanin and Chalikov, 2012, Babanin et al., 2012)

Babanin, A.V., Young, I.R., Phillips, W.R.C., Donelan, A.M., Makin, V., Ardhuin, F. “Oceanic Conditions within Extreme Tropical Cyclones”, ARC Linkage grant. Field investigation of wind input and dissipation in extreme conditions (Toffoli et al. 2012b)

Young, I.R., Babanin, A.V. “A Global Satellite Altimeter Database for Ocean Engineering Applications”, ARC Linkage. Creation of the global altimeter wind and wave database over the period 1985-2008 and investigation global and regional trends (Young et al., 2012)

Young, I.R., Babanin, A.V., Stiassnie, M.A., Greenslade, D.J. “Numerical modelling of extreme waves generated by tropical cyclones”, ARC Discovery. Modelling tropical cyclones, investigation of the nonlinear source term for spectral models (Chalikov and Babanin, 2012)

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